

Foregrounds for 21-cm observations of neutral gas at high redshift

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ABSTRACT

We investigate a number of potential foregrounds for an ambitious goal of future radio telescopes such as the Square Kilometer Array (SKA) and the Low Frequency Array (LOFAR): spatial tomography of neutral gas at high redshift in 21-cm emission. While the expected temperature fluctuations due to unresolved radio point sources is highly uncertain, we point out that free–free emission from the ionizing haloes that reionized the Universe should define a minimal bound. This emission is likely to swamp the expected brightness temperature fluctuations, making proposed detections of the angular patchwork of 21-cm emission across the sky unlikely to be viable. $H\alpha$ observations with JWST could place an upper bound on the contribution of high-redshift sources to the free–free background. An alternative approach is to discern the topology of reionization from spectral features due to 21-cm emission along a pencil-beam slice. This requires tight control of the frequency-dependence of the beam in order to prevent foreground sources from contributing excessive variance. We also investigate potential contamination by galactic and extragalactic radio recombination lines (RRLs). These are unlikely to be show-stoppers, although little is known about the distribution of RRLs away from the Galactic plane. The mini-halo emission signal is always less than that of the intergalactic medium (IGM), making mini-haloes unlikely to be detectable. If they are seen, it will be only in the very earliest stages of structure formation at high redshift, when the spin temperature of the IGM has not yet decoupled from the cosmic microwave background.

Key words: galaxies: formation – cosmology: theory – large-scale structure of Universe.

1 INTRODUCTION

We have as yet no direct observational probes of neutral gas beyond the epoch of reionization. One promising technique which has attracted much attention is 21-cm tomography of neutral hydrogen (Scott & Rees 1990; Madau, Meislin & Rees 1997; Tozzi et al. 2000). 21-cm emission and/or absorption from neutral hydrogen at high redshift should exhibit angular fluctuations as well as structure in redshift space. These fluctuations are due to spatial variations in the hydrogen density, ionization fraction and spin temperature, and may be detectable by future radio telescopes such as the Square Kilometer Array (SKA)¹ and the Low Frequency Array (LOFAR).² Although the energy density in 21-cm emission is about two orders of magnitude less than the cosmic microwave background (CMB), the extreme smoothness of the CMB both spatially and in frequency space would allow this signal to be teased out. The expected brightness temperature fluctuations on arcmin scales is about two orders of magnitude larger than CMB fluctuations. In principle, 21-cm to-

mography would allow us to map out the topology of reionization. This could indirectly constrain the nature of the ionizing sources, telling us whether these sources were faint and numerous or bright and rare. It would thus be an invaluable tool for probing the state of the intergalactic medium during an epoch when traditional probes, such as $Ly\alpha$ absorption, fail (Gunn-Peterson absorption fully saturates at hydrogen neutral fractions $x_{H I} \sim 10^{-4}$).

We present a study of possible foregrounds for these observations. On the arcmin angular scales where the signal is expected to peak, detailed studies of the CMB (involving extrapolation from higher frequencies) tell us that fluctuations in the galactic foreground emission are likely to be relatively unimportant. These galactic foregrounds are fairly well understood, and multifrequency observations should enable us to subtract out both the free–free and synchrotron components (see Shaver et al. 1999 for a detailed discussion). Unresolved extragalactic radio sources, on the other hand, could give rise to brightness temperature fluctuations which would swamp the expected signal, as discussed by Di Matteo et al. (2002). However, this model for source counts was based on surveys with limiting flux densities ~ 100 mJy at 150 MHz, which were then extrapolated down five orders of magnitude past ~ 1 μ Jy (the expected limiting point source sensitivity of SKA). Therefore, as they acknowledge, this estimate of foreground contamination is highly uncertain; a

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¹ see <http://www.skatelescope.org>

² see <http://www.lofar.org>

turnover in source counts at lower flux levels could significantly reduce foreground contamination.

We present a *minimal* estimate of the brightness temperature fluctuations, based on free–free emission from the ionizing sources that reionized the Universe (Oh 1999). We show that brightness temperature fluctuations from these sources exceed the expected signal, making it unlikely that the previously proposed angular 21-cm tomography is feasible. We shall show that this estimate is relatively model-independent and depends primarily on the integrated ionizing emissivity.

An inability to detect angular brightness temperature fluctuations need not render 21-cm tomography studies powerless. Because the foreground signal is expected to be smooth in frequency space, 21-cm spectral features along a pencil-beam slice, corresponding to alternating patches of neutral and ionized hydrogen, could yield invaluable information on the topology of reionization. However, this relies heavily on the lack of foreground spectral contaminants. We investigate two possible contaminants: spectral fluctuations in the foreground due to the frequency-dependent beam, and radio recombination lines from galactic and extragalactic ionized gas. The former can probably be dealt with if the frequency dependence of the beam can be controlled and its side-lobes mapped out. The latter is much more uncertain but is unlikely to be a show-stopper. If, in fact, it does turn out to be important, it will yield the unexpected bonus of new information about the clumping of ionized gas in our Galaxy and in the Universe as a whole.

In all numerical estimates, we assume a Λ CDM cosmology where $(\Omega_m, \Omega_\Lambda, \Omega_b h^2, h, \sigma_{8h^{-1}}) = (0.3, 0.7, 0.019, 0.7, 0.9)$.

2 FREE–FREE EMISSION FROM IONIZING SOURCES AS A FOREGROUND

We begin by summarizing the properties of the expected signal; the reader is referred to the literature (Scott & Rees 1990; Madau et al. 1997; Tozzi et al. 2000) for details. Consider a patch of intergalactic medium (IGM), with spin temperature T_S , which fully fills the beam and has a radial velocity width larger than the bandwidth of the radio telescope. The differential brightness temperature between this patch and the CMB is (Tozzi et al. 2000):

$$\delta T_b \approx 9.0 \text{ mK } h^{-1} \left(\frac{\Omega_b h^2}{0.02} \right) \left(\frac{1+z}{10} \right)^{1/2} \left(\frac{T_S - T_{\text{CMB}}}{T_S} \right). \quad (1)$$

Of course, if ionized bubbles exist within this patch then the signal will be diluted by the corresponding filling factor.

Initially, $T_S = T_{\text{CMB}}$, but over time $\text{Ly}\alpha$ photons from the soft ultraviolet (UV) background emitted by the first stars and quasars will couple the spin temperature of the gas to its kinetic temperature through the Wouthuysen–Field effect. Because $T_K < T_{\text{CMB}}$ initially, neutral hydrogen will be visible for a brief period in absorption until the same $\text{Ly}\alpha$ photons also heat the gas through recoil of the scattered $\text{Ly}\alpha$ photons and make $T_S > T_{\text{CMB}}$. At this point the signal is only visible in emission; from equation (1) the brightness temperature is roughly independent of the spin temperature. Hereafter, we shall focus solely on the emission signal.

If linear theory is used to compute expected density fluctuations, the brightness temperature fluctuations peak on arcmin scales and have a rms value of $\langle \delta T_b^2 \rangle^{1/2} \approx 10 \text{ mK}$ for a Λ CDM cosmology (see fig. 1 of Tozzi et al. 2000). To give a sense of the length-scales involved, a bandwidth $\Delta\nu$ corresponds to a comoving length $L \approx (1+z)cH(z)^{-1}\Delta\nu/\nu = 8.6(1+z/10)^{-3/2}(\Delta\nu/1 \text{ MHz}) h^{-1} \text{ Mpc}$, where $\nu = 1.4/(1+z) \text{ GHz}$ is the observation frequency, and an

angular diameter $\Delta\theta$ corresponds to a comoving transverse length $L = \Delta\theta(1+z)/d_A(z) \approx 1.9(\Delta\theta/1') h^{-1} \text{ Mpc}$ at $z = 9$.

The contribution of radio-loud active galactic nuclei (AGN) and radio galaxies at low flux levels is highly uncertain. We therefore construct a minimal model of the low-frequency radio background from free–free emission by ionizing sources. This background is *unavoidable*, in the sense that a minimal emissivity in ionizing photons is necessary to reionize the Universe. We present a brief summary here; refer to Oh (1999) for details. The free–free luminosity of an ionizing source can be estimated as follows. Most of the free–free emission comes from H II regions in the protogalaxy where ionizations balance recombinations (we do not consider free–free emission from hot gas within the halo, which provides a smaller additional contribution). The free–free volume emissivity for a plasma is (Rybicki & Lightman 1979):

$$\epsilon_\nu = 3.2 \times 10^{-39} n_e^2 \left(\frac{T}{10^4 \text{ K}} \right)^{-0.35} \text{ erg s}^{-1} \text{ cm}^{-3} \text{ Hz}^{-1}, \quad (2)$$

where we adopt the velocity-averaged Gaunt factor $\bar{g}_{\text{ff}} = 4.7$ and approximate its mild temperature dependence with a power law (note that the temperature $T \sim 10^4 \text{ K}$ is not the virial temperature of the halo but the temperature of the H II region). Because $L_{\text{ff}} = \int \epsilon_\nu dV \propto \langle n_e^2 \rangle V \propto \dot{N}_{\text{rec}}$, we need to estimate the total recombination rate \dot{N}_{rec} . It is directly related to the production rate of ionizing photons \dot{N}_{ion} by:

$$\dot{N}_{\text{rec}} = \alpha_B \langle n_e^2 \rangle V \approx (1 - f_{\text{esc}}) \dot{N}_{\text{ion}} \quad (3)$$

where α_B is the case B recombination coefficient, and f_{esc} is the escape fraction of ionizing photons. We thus obtain for the free–free luminosity:

$$L_v^{\text{ff}} \approx 1.1 \times 10^{27} \left(\frac{\dot{N}_{\text{ion}}}{10^{53} \text{ photon s}^{-1}} \right) \left(\frac{1 - f_{\text{esc}}}{0.9} \right) \text{ erg s}^{-1} \text{ Hz}^{-1}. \quad (4)$$

where we have dropped the weak temperature dependence of the free–free emissivity. Similar to the recombination line luminosity (which also scales as $\langle n_e^2 \rangle V$), the free–free luminosity scales directly with the production rate of ionizing photons, independent of the details of the host halo. For a Salpeter IMF with stars of solar metallicity, $N_{\text{ion}} = 10^{53} \text{ photon s}^{-1}$ ($\text{SFR}/1 \text{ M}_\odot \text{ yr}^{-1}$). For a given star formation rate (SFR), stars with zero metallicity can be one to two orders of magnitude more effective at producing ionizing photons, as the effective temperature of these stars is higher (Tumlinson & Shull 2000) and the IMF of zero-metallicity stars is often thought to be top-heavy. The escape fraction of ionizing photons is observed to be $f_{\text{esc}} \sim 5$ per cent in the local Universe (Leitherer et al. 1995), and thought to decline with redshift (Wood & Loeb 2000; Ricotti & Shull 2000), although this is highly uncertain (for calculations arriving at the opposite conclusion, see Fujita et al. 2002). The observed free–free flux is then given by $S_{\text{ff}} = L_v^{\text{ff}}(1+z)/4\pi d_L^2$, or:

$$S_{\text{ff}} \approx 1.2 \left(\frac{1+z}{10} \right)^{-1} \left(\frac{\dot{N}_{\text{ion}}}{10^{53} \text{ photon s}^{-1}} \right) \left(\frac{1 - f_{\text{esc}}}{0.9} \right) \text{ nJy}. \quad (5)$$

Note that the uncertainty in the escape fraction of ionizing photons introduces uncertainties of at most a factor of only a few in the free–free luminosity. Only in the unlikely scenario of virtually all the ionizing photons escaping into the IGM without any photoelectric absorption in the host interstellar medium (ISM), would order of magnitude uncertainties creep in as $f_{\text{esc}} \rightarrow 1$.

To compute the brightness temperature fluctuations due to these sources, we need to construct a luminosity function. Oh (1999) followed the star formation model of Haiman & Loeb (1997), who

assumed that some constant fraction of the gas f_* in haloes with virial temperatures $T_{\text{vir}} > 10^4$ K fragments to form stars, and that each starburst lasts for $\sim 10^7$ yr. The star formation efficiency parameter f_* is tuned for consistency with the observed metallicity of the IGM at $z = 3$, with $f_* \sim 1.7$ –17 per cent corresponding to $Z \sim 10^{-3}$ – $10^{-2} Z_{\odot}$, respectively. With this prescription, $\dot{N}_{\text{ion}} \approx 2 \times 10^{53} (M_{\text{halo}}/10^9 M_{\odot}) \text{ photon s}^{-1}$. Press–Schechter theory can be used to compute the abundance of haloes and hence the source counts dN/dS . The power spectrum of Poisson fluctuations can then be computed from:

$$C_1^{\text{Poisson}} = \int_0^{S_c} dS \frac{dN}{dS} S^2 \quad (6)$$

where S_c is the minimal flux above which point sources can be identified and removed. The power spectrum due to clustering can be computed from:

$$C_1^{\text{clustering}} = w_1 I_{\nu}^2 \quad (7)$$

where w_1 is the Legendre transform of the angular correlation function of sources $w(\theta)$, and $I_{\nu} = \int_0^{S_c} dS (dN/dS) S$ is the surface brightness of the radio background at frequency ν . The spatial correlation length can be computed from linear theory assuming linear bias; the decrease in the linear growth factor at high-redshift is increased by the number-weighted bias of objects with $T_{\text{vir}} > 10^4$. This results in an angular correlation function $w(\theta) = (\theta/\theta_o)^{-0.8}$ with a nearly constant angular correlation length $\theta_o \sim 2$ arcmin, independent of redshift for $z > 3$ (see fig. 5 of Oh 1999). The rms temperature fluctuations can then be computed from $T_{\text{rms}} = [l(l+1)C_l/4\pi]^{1/2} \times c^2/2k_B\nu^2$, where the frequency dependence of the temperature conversion is appropriate in the Rayleigh–Jeans limit. This quadratic frequency dependence implies that the population of free–free emitters only becomes important at low frequencies. Thus, for instance, their existence does not violate any present CMB distortion constraints.

What is the minimal flux S_c above which point sources can be identified and removed? The detector noise is (Rohlfs & Wilson 1996):

$$S_{\text{inst}} = \frac{2kT_{\text{sys}}}{A_{\text{eff}}\sqrt{2t\Delta\nu}} \sim 0.3 \left(\frac{\Delta\nu}{1 \text{ MHz}} \right)^{-1/2} \left(\frac{t}{10^5 \text{ s}} \right)^{-1/2} \mu\text{Jy} \quad (8)$$

where we have used $A_{\text{eff}}/T_{\text{sys}} = 2 \times 10^8 \text{ cm}^2 \text{ K}^{-1}$. On the other hand, the signal-to-noise ratio (S/N), if confusion noise dominates, is:

$$\frac{S}{N} = \frac{S_c}{[C_1^{\text{clustering}}(S_c)\theta^2]^{1/2}} \approx 10 \left(\frac{S_c}{20 \text{ nJy}} \right)^{0.7} \left(\frac{\theta}{0.3 \text{ arcsec}} \right)^{-1.6} \quad (9)$$

Thus, for a 10σ detection of a source, the cut-off flux is $S_c \sim 20$ nJy. Note that $S_{\text{conf}} \propto [C_1^{\text{clustering}}(S_c)]^{1/2} \propto S_c^{0.3}$ depends only weakly on the flux cut-off (see Fig. 1 of this paper and also fig. 4 of Oh 1999). This is because $C_1^{\text{clustering}} \propto I_{\nu}^2(S_c)$, and from equation (5) the majority of sources which constitute the free–free background are generally fainter than ~ 20 nJy; removal of rare bright sources has little effect on the mean free–free background I_{ν} . We have assumed unresolved point sources so that θ is given by the beam resolution; the confusion noise becomes correspondingly larger if the source is extended.

Confusion noise, rather than instrumental noise, is the limiting factor in source identification and removal for free–free sources. The free–free flux is largely frequency-independent. If instrumental noise were the limiting factor, point sources could be identified and removed with higher frequency observations, for which instrumental

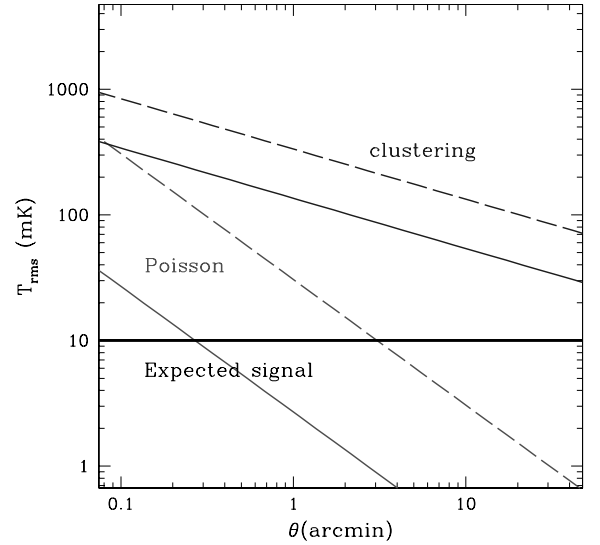


Figure 1. Brightness temperature fluctuations induced by free–free emission from ionizing sources, compared with the expected 21 cm signal, at a frequency of 150 MHz (corresponding to an observed redshift of $z = 8.3$), and assuming a star formation efficiency corresponding to a Ly α forest metallicity of $Z = 10^{-2.5} Z_{\odot}$ at $z = 3$. Solid and dashed lines assume point source removal down to 20 nJy and 2 μ Jy respectively. The 21-cm signal is likely to be swamped by fluctuations due to clustering of the free–free sources at all scales. The estimate for the clustering component is fairly robust and model-independent (see text). Note that $T_{\text{rms}}^{\text{clustering}} \propto \Omega_*(z=3) \propto Z(z=3)$.

noise is much lower (for instance, in 10 d a 5σ detection of a 16-nJy source at 2 GHz is possible, for a bandwidth $\Delta\nu = 1$ GHz). However, as confusion noise is frequency-independent, once the confusion limit is reached no further source removal is possible, even with multifrequency observations.

We compute the Poisson and clustering contributions to the free–free background with the above model. The results are displayed in Fig. 1. The 21-cm signal is likely to be swamped by Poisson fluctuations at small scales and by fluctuations due to clustering of free–free sources at all scales. This calculation should be compared with that of Di Matteo et al. (2002), who use a power-law extrapolation of observed number counts to compute the same quantities. Although we arrive at similar conclusions, below we argue that these estimates (in particular the temperature fluctuations due to the clustering component) are significantly more robust.

The results obviously depend on the specifics of the star formation model assumed. Because this is highly uncertain, we highlight here the most robust features of the calculation, which are largely model-independent. The number counts in the Poisson signal are dominated by rare bright objects just below the detection threshold S_c , and can vary widely depending on the shape of the luminosity function at these low flux levels. We therefore disregard this term as it is excessively model-dependent. On the other hand, the clustering term (equation 7) is significantly more robust. Our estimate of $\theta_o \sim 2$ arcmin is probably a minimal estimate of the angular clustering strength, as it is dominated by the bias of haloes at the threshold virial temperature $T_{\text{vir}} \sim 10^4$ K, which are most abundant. Star formation in lower virial temperature haloes, which cannot cool by atomic line cooling, is expected to be extremely inefficient; see e.g. Barkana & Loeb (2001) for a general review. If, in fact, star formation is more efficient in deeper potential wells (e.g. because feedback processes are less devastating there), the luminosity-weighted

correlation function will be more heavily weighted towards rare massive haloes, which are more highly biased. Thus, the w_1 term is generally a minimal estimate. Note that any alterations to canonical CDM models which reduce small-scale power (e.g. a tilt in the power spectrum) will generally favour rarer, more highly biased sources which increase w_1 .

The surface brightness term I_ν^2 is independent of the model for the luminosity function and/or structure formation model. It depends only on the overall normalization of the comoving luminosity density. We can see this from the equation of cosmological radiative transfer (Peebles 1993):

$$I(\nu_o) = \frac{c}{4\pi} \int_0^\infty dz \frac{dt}{dz} \frac{\epsilon[\nu_o(1+z)]}{(1+z)^3}, \quad (10)$$

where $\epsilon(\nu)$ is the comoving emissivity. Because $\epsilon \propto \dot{\Omega}_*(1 - f_{\text{esc}})$ (from equation 5), the radio surface brightness $I(\nu_o) \propto \Omega_*(1 - f_{\text{esc}})/(1+\bar{z})^3$, where \bar{z} is the median redshift at which ~ 50 per cent of all stars have formed. Thus, a given comoving stellar density Ω_* directly and robustly implies a minimal free-free surface brightness on the sky (the dependence on the star formation history $\dot{\Omega}_*(z)$ is weak, as most stars formed at late times). In our calculation we have conservatively included only sources at $z > 3$ (which are too faint to be identified and removed) and simply normalized to $\Omega_*(z=3) = 6 \times 10^{-3} (\bar{Z}/10^{-2.5} Z_\odot) \Omega_b$, where \bar{Z} is the mean metallicity of the IGM at $z \sim 3$, and we assume a Salpeter IMF where $\sim 1 M_\odot$ of metals form for every $\sim 100 M_\odot$ of stars formed. Alternatively, one can normalize high-redshift star formation to the reionization optical depth detected by *WMAP* $\tau \sim 0.17 \pm 0.04$ (Spergel et al. 2003; Kogut et al. 2003), which gives similar results (e.g. see Oh, Cooray & Kamionkowski 2003). As previously noted, because the majority of sources are significantly fainter than the threshold flux for point source removal S_c , the mean surface brightness depends only weakly on S_c (see fig. 4 of Oh 1999).

Both the estimates for the clustering strength w_1 and the mean surface brightness I_ν are minimal and robust. We therefore conclude that our estimate for C_1^{cluster} constitutes a robust *minimal* estimate for angular temperature fluctuations on the sky. These fluctuations will swamp the expected brightness temperature fluctuations due to 21-cm emission by at least an order of magnitude.

One possible way to constrain the free-free background from high-redshift is to use $H\alpha$ observations with the James Webb Space Telescope (JWST), as $L_{H\alpha} \propto L_{\text{ff}}$ (Oh 1999). The IGM will still be optically thin to $H\alpha$ photons in the pre-reionization epoch (unlike the case for $\text{Ly}\alpha$ photons). Indeed, because JWST can detect sources with 100–1000 lower star formation rates in $H\alpha$ emission than SKA can detect in free-free emission (see equation 21 of Oh 1999), the JWST can probe far down the luminosity function to determine if unresolved high-redshift sources in radio maps are indeed responsible for observed brightness temperature fluctuations. Because the JWST has a much smaller field of view (5 arcmin) than the SKA (1°), the JWST will likely only be useful in masking out foreground sources on small scales. None the less, observations with JWST will certainly be able to place an upper limit on the free-free background due to high-redshift sources, allowing us to distinguish brightness temperature fluctuations due to free-free sources and due to 21-cm emission from the neutral IGM.

Unlike 21-cm emission, free-free emission produces a flat featureless continuum. The free-free background therefore does not have any sharp features in frequency space, whereas 21-cm emission does (in particular, there is no spectral feature in the free-free background associated with the end of reionization). We

now turn to the prospects for spectral measurements of 21-cm emission.

3 FOREGROUNDS FOR SPECTRAL MEASUREMENTS

Even if brightness temperature fluctuations due to 21-cm emission are not detectable, spectral variation along a pencil-beam might still be detected. This relies on the fact that foreground sources should in general have smooth power-law continuum spectra, and averaging over many sources with different spectral indices and spectral structure will yield a smooth power-law foreground (see Shaver et al. 1999 for simulations of this) which would still allow detection of spectral structure corresponding to alternating regions of neutral and ionized hydrogen. To give an idea of scale, an ionized ‘bubble’ created by a source forming stars at a rate $\sim 2 M_\odot \text{ yr}^{-1}$ for $\sim 10^7$ yr has a diameter $\sim 1.4[(1+z)/10]^{-1} h^{-1} \text{ Mpc}$ comoving, while a bandwidth $\Delta\nu$ spans a comoving length $L \approx 8.6(1+z/10)^{-3/2} (\Delta\nu/1 \text{ MHz}) h^{-1} \text{ Mpc}$. Of course, as reionization proceeds the ionized regions expand in size and neutral regions contract. As Di Matteo et al. (2002) point out, observing with 2-MHz resolution at $\nu_o = 150 \text{ MHz}$ with an error of $\Delta\beta \sim 0.05$ in the measured foreground spectrum spectral slope should allow one to distinguish a signal that is $[(\nu/\nu_o)^{\Delta\beta} - 1] \sim 6 \times 10^{-4}$ times smaller than the foreground. Here, we discuss two potential foregrounds for such spectral measurements: beam smearing of foreground sources and radio recombination lines.

The radio telescope does not sample exactly the same patch of sky at all frequencies, because the beam-size and sidelobes are frequency dependent. This would by itself naturally introduce frequency space fluctuations in the measured brightness temperature as additional sources fill the beam, an effect of order:

$$\begin{aligned} \left(\frac{\Delta T}{T} \right)_{\text{fg}} &\sim \frac{\Delta\Omega}{\Omega} \sim 2 \frac{\Delta\theta}{\theta} \sim 2 \frac{\Delta\nu}{\nu} \\ &\sim 1.4 \times 10^{-2} \left(\frac{\Delta\nu}{2 \text{ MHz}} \right) \left(\frac{1+z}{10} \right). \end{aligned} \quad (11)$$

As we have seen that the clustering foreground $\langle T_{\text{fg}}^2 \rangle^{1/2} \gtrsim 10 \langle T_{21\text{cm}}^2 \rangle^{1/2}$, the noise in frequency space introduced by beam-size variation will be $\delta T_{\text{fg}} \sim \text{few} \times 0.1 \langle T_{21\text{cm}}^2 \rangle^{1/2}$, comparable to temperature fluctuations due to 21-cm emission. An exception may be in the very early/late stages of reionization, when the size of ionized/neutral patches is small; the beamsizes does not vary significantly over the small bandwidth $\Delta\nu$ necessary to detect spectral features. Otherwise, it would be necessary to develop scaled beams and controlled sidelobes, which are capable of sampling exactly the same patch of sky at all frequencies. Note that frequency calibration of the telescope for pencil beam tomography is considerably more challenging than frequency calibration for detecting an all-sky signal, such as that produced at the tail end of reionization (Gnedin & Ostriker 1997). In the case of an all-sky signal, one could simply average the results over many independent patches of sky, as well as perform a differencing experiment off the moon, which blocks emission behind it (Shaver et al. 1999).

Another possible source of structure in frequency space is the signal from radio recombination lines (RRLs). These lines have been observed both in emission and absorption at a wide range of frequencies, although generally only against bright sources in the Galactic plane (see Gordon & Sorooshenko 2002 for a comprehensive review). The frequencies of the hydrogen lines are:

$$\nu \approx 153 \Delta n \left(\frac{n}{350} \right)^{-3} \text{ MHz.} \quad (12)$$

The important question is whether RRLs will provide a significant source of contamination on lines of sight outside the Galactic plane. There have been few RRL line searches away from bright sources outside the Galactic plane, and in any case surveys for radio recombination lines generally have low-frequency detection limits above the strength of the 21 cm features we seek. We can place a useful limit using the fact that the observed brightness of both RRL and H α emission depends on the emission measure $EM = \int ds n_e^2$, and that optical surveys for H α have much lower limiting sensitivities. Fabry–Perot surveys have detected H α emission from every Galactic latitude, with minimal values 0.25–0.8 Rayleighs toward the Galactic pole (Reynolds 1990). The emission measure corresponding to an observed H α intensity I_α (in Rayleighs) is: $EM(H\alpha) = 2.75 T_e^{0.9} I_\alpha \text{ cm}^{-6} \text{ pc}$. Based on the width of the H α line, Reynolds (1990) estimates $T \sim 8000 \text{ K}$. Given the density, temperature and size of a region, as well as an estimate of the linewidth and a frequency to observe at, one can also calculate the recombination line optical depth (Shaver 1975):

$$\tau_L = \frac{518 EM}{\nu \Delta V_L T_e^{5/2}} b_n \left[1 - 20.8 \frac{T_e}{\nu} \frac{d \ln b_n}{dn} \right],$$

where EM is the emission measure in $\text{cm}^{-6} \text{ pc}$ defined by $n_e^2 l$, ν is the line centre frequency, V_L is the linewidth in km s^{-1} , T_e is the electron temperature, and b_n is the departure coefficient, which takes into account departures from local thermodynamic equilibrium (LTE). For LTE, $b_n \equiv 1$. For an unresolved line, the velocity width is simply $\Delta V_L = c(\Delta \nu / \nu)$, where $\Delta \nu$ is the observational bandwidth. Assuming $I_\alpha = 0.25 R$ (which corresponds to $EM = 0.5 \text{ cm}^{-6} \text{ pc}$) and $T_L = \tau_L T_e$, we can employ the optical depth calculation to estimate the hydrogen RRL temperature:

$$T_L = 1.3 \times 10^{-6} \left(\frac{T_e}{8000 \text{ K}} \right)^{-3/2} \left(\frac{EM}{0.5 \text{ cm}^{-6} \text{ pc}} \right) \times \left(\frac{\Delta \nu}{1 \text{ MHz}} \right)^{-1} \text{ K,} \quad (13)$$

which is negligible. Note, however, that this estimate assumes thermodynamic equilibrium. Particularly for lower frequency lines, stimulated emission may become important.

Carbon radio recombination lines are another possible source of contamination. They have been detected in the frequency range 34–325 MHz toward Cass A in the Galactic plane (Payne, Anantharamaiah & Erickson 1989), and also in a 327-MHz survey centred at $b = 14^\circ$ (Roshi et al. 2002). Optical depths are generally $\tau \sim 10^{-3}$ and they are thought to arise in dense, cold ($T_e \sim 20\text{--}200 \text{ K}$), partially ionized regions where non-LTE effects are important. Carbon RRL emission is generally confined to $b < 3^\circ$ and their intensity out of the plane is probably small (Roshi et al. 2002).

Detections of radio recombination lines from extragalactic sources have generally been confined to bright starburst galaxies, and the intensity appears to be correlated with the star formation rate (Phookun, Anantharamaiah & Goss 1998). They are unlikely to be significant contaminants. One can show that for reasonable assumptions about the excitation parameter only nearby sources ($D \leq 10 \text{ Mpc}$) will be detectable in RRL emission if spontaneous emission is responsible (Shaver 1978). It was thought that stimulated emission could allow observation of much more distant sources (Shaver 1978), but that has not turned out to be the case.

Extragalactic RRLs could be a foreground in the search for 21-cm absorption against radio-loud sources at high redshift (Carilli, Gnedin & Owen 2002; Furlanetto & Loeb 2002). Because high-redshift objects are in general much denser $n_e^2 \propto (1+z)^6$, their emission measures are much higher. Consider an isothermal disc at temperature T_{gas} embedded in a halo with virial temperature T_{vir} . One can solve for the density profile of such a disc, $n \propto \exp(-r/R_d) \text{sech}^2(z/z_o)$ (Wood & Loeb 2000; see also Oh & Haiman 2002), and the emission measure of the disc will be $EM(r) \approx \int dz n^2(r, z)$. For a disc seen face-on, the emission measure becomes a function of the radial distance r from the centre:

$$EM(r) \approx 2 \times 10^9 \left(\frac{f_d}{0.5} \right)^3 \left(\frac{T_{\text{gas}}}{10^4 \text{ K}} \right)^{-1} \left(\frac{T_{\text{vir}}}{5 \times 10^4 \text{ K}} \right)^{3/2} \times \left(\frac{\lambda}{0.05} \right)^{-6} \left(\frac{1+z}{10} \right)^{9/2} \exp \left(-\frac{2r}{R_d} \right) \text{ cm}^{-6} \text{ pc,} \quad (14)$$

where $f_d = (M_{\text{disc}}/M_{\text{halo}})/(\Omega_b/\Omega_o)$ is the fraction of baryons in the disc, λ is the spin parameter and $R_d \approx \lambda r_{\text{vir}}/\sqrt{2}$. The optical depth at line centre for a $\Delta n = 1$ RRL will be:

$$\tau_L = 2 \times 10^{-2} \left(\frac{T_e}{10^4 \text{ K}} \right)^{-5/2} \left(\frac{EM}{10^8 \text{ cm}^{-6} \text{ pc}} \right) \left(\frac{\Delta \nu}{1 \text{ MHz}} \right)^{-1}, \quad (15)$$

assuming local thermodynamic equilibrium and that the line is unresolved. This could be considerably enhanced if stimulated emission and/or non-LTE effects become important (which is likely because one is looking along the line of sight to a radio-bright source). This optical depth is comparable to the central optical depths due to 21-cm absorption by the IGM (Carilli et al. 2002) or mini-haloes/mini-discs (Furlanetto & Loeb 2002), which are of order $\tau \sim 10^{-2}$. If one uses Press–Schechter theory to calculate abundances of haloes with $T_{\text{vir}} > 10^4 \text{ K}$, a random line of sight would intersect $\sim \text{few} \times 0.1$ discs per redshift interval, for the redshifts of interest (Furlanetto & Loeb 2002). Even a single disc along the line of sight would introduce a plethora of RRL features in emission and/or absorption. This would make the task of picking out the spectral features due to 21-cm absorption much more difficult. On the other hand, such observations would also be an invaluable probe of gas clumping at high redshift. However, this is a rather speculative scenario, and we shall not comment on it further.

In general, radio recombination lines are unlikely to be significant contaminants. If they are, they will have to be removed with observations of higher spectral resolution (using the fact that they occur at known frequency intervals for identification and removal). In many ways their detection could be an unexpected bonus, as RRLs have the potential to teach us a great deal about the clumping of ionized gas, both within our Galaxy and in the Universe as a whole.

4 DETECTION OF MINI-HALOES

Recently, it has been proposed that mini-haloes with $T < 10^4 \text{ K}$, which are not collisionally ionized but which have gas densities sufficiently high to collisionally couple the spin temperature to the kinetic temperature, may be detectable in emission (Iliev et al. 2002, 2003). For $T_S \gg T_{\text{CMB}}$, the flux is independent of the spin temperature and depends only on the H I mass. Although the signal from an individual mini-halo is very faint, the combined signal from many mini-haloes within a sufficiently large comoving volume may be detectable. We point out that because $S_\nu \propto M_{\text{H I}}$, the flux from mini-haloes will always be swamped by the flux from the neutral IGM, as the H I mass in the IGM is larger. The ratio of fluxes is given by the relative fraction of H I in collapsed haloes with $T_{\text{vir}} < 10^4 \text{ K}$:

$$\frac{S_{\nu}^{\text{haloes}}}{S_{\nu}^{\text{IGM}}} \approx \frac{\Omega_{\text{H I,haloes}}}{\Omega_{\text{H I}}} \approx \frac{1}{\rho_m} \int_{M_{\text{low}}}^{M_{\text{high}}} dM \frac{dN}{dM} M, \quad (16)$$

where dN/dM is the halo abundance given by Press–Schechter theory, $M_{\text{high}} = 10^8[(1+z)/10]^{-3/2} M_{\odot}$ is the mass of haloes with $T_{\text{vir}} = 10^4$ K and M_{low} is the baryonic Jeans mass below which gas cannot accrete on to haloes. If there is no heating of the IGM, M_{low} is given by the cosmological Jeans mass $M_J = 8 \times 10^3[(1+z)/10]^{3/2} M_{\odot}$, where the temperature of the IGM $T_{\text{IGM}} = 1.7[(1+z)/10]^2$ K is simply set by the amount of adiabatic cooling since decoupling from the CMB. In reality it is likely that the gas will be heated up to higher temperatures by soft X-ray and Ly α photon recoil heating from the first sources of light, as well as by free–free emission from collapsing structures (Madau et al. 1997). In addition, relic H II regions which have recombined after their ionizing source shut off will have a finite temperature and entropy, as Compton cooling is only efficient down to some temperature T_{min} , below which the gas recombines and decouples from the CMB (Oh & Haiman 2003). This will suppress the accretion of gas on to the smallest mini-haloes. We can crudely model the cut-off by specifying a new Jeans mass M_{low} for the higher IGM temperature. This corresponds to a virial temperature $T_{\text{vir}} \approx 100^{2/3} T_{\text{IGM}} \approx 20 T_{\text{IGM}}$ (this roughly corresponds to haloes which can attain a baryonic overdensity of $\delta_b \sim 100$; see section 3.2 of Barkana & Loeb 2001). We develop a more sophisticated model of gas accretion on to mini-haloes in the presence of an entropy floor in Oh & Haiman (2003); see section 4.1 in that paper for a more sophisticated calculation of the collapsed gas fraction in mini-haloes.

We plot the ratio of fluxes from equation (16) in Fig. 2. Even if heating is negligible, this ratio is at most a few $\times 0.1$. This may be amplified in high-density peaks by a factor of no more than a few due to clustering bias (Iliev et al. 2003). Even a small amount of heating

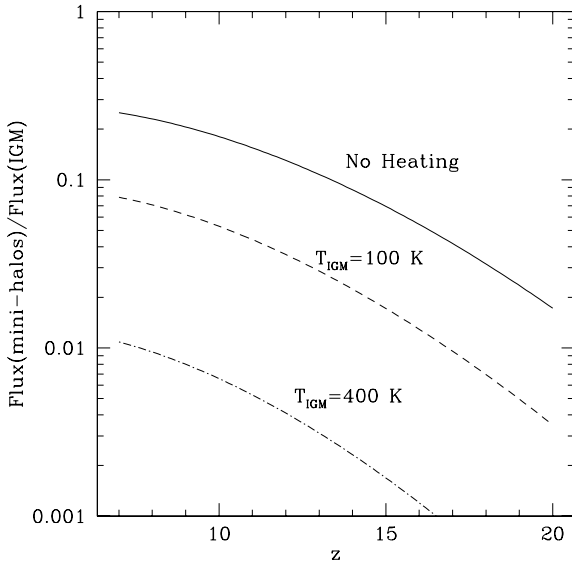


Figure 2. Relative 21-cm flux from mini-haloes compared to IGM in a neutral patch which fills the beam, assuming $T_S \gg T_{\text{CMB}}$ for both. Because $S_{\nu}^{\text{haloes}}/S_{\nu}^{\text{IGM}} = \Omega_{\text{haloes}}/\Omega_b$, the 21-cm emission from the IGM will always be greater except in the earliest stages of structure formation when the spin temperature of the IGM is still coupled to that of the CMB. The relative mass fraction (and hence 21-cm flux) in mini-haloes decreases still further if the IGM is heated to ‘warm’ temperatures (e.g. $T_{\text{IGM}} \sim 100$ K, 400 K as shown here) by soft X-rays, atomic recoil from Ly α photon scattering, or by residual entropy in relic H II regions. The higher temperature increases the baryonic Jeans mass and suppresses accretion on to mini-haloes.

vastly reduces the collapsed gas fraction in minihaloes, and strongly attenuates the mini-halo 21-cm signal. Thus, the flux from mini-haloes only dominate in two limits: (i) in reionized regions, for self-shielded mini-haloes which have not yet been photo-evaporated, and (ii) very early in the structure formation process, when the background radiation field is low, the spin temperature of the IGM is still coupled to that of the CMB, and the filling factor of relic H II regions is small. The former case is unlikely to be detectable as the mini-haloes contribute a small signal superimposed on the much larger fluctuating signal of alternating neutral and ionized regions of the IGM. The latter may be detectable provided the mini-haloes indeed remain neutral and do not form stars via H₂ cooling: even a single star in a halo is capable of photo-ionizing and photo-evaporating much of the gas.

It is worth checking if this is possible. From Haiman, Abel & Rees (2000) (see their fig. 6), the level of background UV flux capable of photodissociating H₂ in mini-haloes and preventing star formation is:

$$J_{\text{diss}} \sim 10^{-3} - 10^{-2} J_{21} \quad (17)$$

in the redshift range $z = 10$ – 20 where J_{21} (in units of 10^{-21} erg s^{−1} cm^{−2} Hz^{−1} sr^{−1}) is the UV flux in the Lyman–Werner bands 11.2–13.6 eV. On the other hand, the critical thermalization flux of Ly α photons (which consists of redshifted photons from the Lyman–Werner bands) required to decouple the spin temperature of the IGM from the CMB and drive $T_S \rightarrow T_K$ is (Madau et al. 1997):

$$J_{\text{therm}} \approx 0.9 J_{21} \left(\frac{1+z}{10} \right). \quad (18)$$

Because $J_{\text{diss}} \ll J_{\text{therm}}$, there certainly exists a period in the history of the IGM where gas in mini-haloes cannot cool to form stars, but the IGM does not emit in 21-cm radiation. In this case, the haloes would give rise to a period in which 21 cm is detectable in emission before it is seen in absorption when $T_{S,\text{IGM}} < T_{\text{CMB}}$. 21-cm radiation would once again be detectable in emission due to heating when $T_{S,\text{IGM}} \gg T_{\text{CMB}}$. The duration of each of these epochs can be used to time the rise of the radiation field. Of course, this is all assuming that the noise from foregrounds previously discussed can be overcome for the smaller signal levels expected from mini-haloes. Note that a period of early reionization would wipe out the mini-halo population by raising the baryonic Jeans mass (Cen 2003; Oh & Haiman 2003); as noted by Oh & Haiman (2003), mini-haloes will only be present in tracts of the IGM which have *never* been previously ionized. Also, early star formation would provide trace metal contamination, and if $Z \gtrsim 10^{-3} Z_{\odot}$ (Bromm et al. 2001), the gas in mini-haloes would be able to cool via metal line cooling and form stars. If the mini-halo signal is detectable in spectral pencil-beam measurements, it is preferable to have as small a bandwidth as possible (~ 0.1 MHz) to maximize intensity fluctuations due to the varying number of haloes within a bandwidth along the line of sight.

5 CONCLUSIONS

We have considered a number of foregrounds for 21-cm emission studies. We perform a robust minimal estimate of temperature fluctuations across the sky due to free–free emission by ionizing sources assuming only: (i) a number-weighted clustering bias with a cut-off for haloes with $T_{\text{vir}} < 10^4$ K, (ii) a star formation history normalized to the metallicity of the $z = 3$ Ly α forest, and (iii) an escape fraction of ionizing photons into the IGM of no more than $\sim \text{few} \times 0.1$. We conclude that the clustering component of temperature

fluctuations will swamp the expected angular brightness temperature fluctuations due to 21-cm emission during the cosmological Dark Ages by at least an order of magnitude. A firm upper limit to the free-free background from high-redshift can likely be obtained with H α observations by JWST, because $L_{\text{ff}} \propto L_{\text{H}\alpha}$. JWST can detect sources with much lower star formation rates in H α emission than detectable by SKA in free-free emission, and hence will be able to resolve out most of the sources responsible for the free-free background.

Performing 21-cm tomography by detecting spectral features along a single line of sight requires developing scaled beams which sample exactly the same patch of sky at all frequencies. Otherwise, excess variance in foreground sampling due to the frequency dependence of the beam will swamp the signal. Note that such considerations only affect 21-cm tomography, and not an all-sky signal such as expected at the tail end of reionization (Baltz, Gnedin & Silk 1998; Shaver et al. 1999). We also discuss radio recombination lines as possible contaminants. It is unlikely that this will be a problem for surveys outside of the Galactic plane, although this is still fairly uncertain.

Because the 21-cm flux is directly proportional to H I mass, the mini-halo 21-cm emission signal is always less than that of the IGM, making isolation of the mini-halo signal difficult. If mini-haloes are seen, it will be only be during a special epoch in the early stages of structure formation, when the UV radiation field is strong enough to suppress gas cooling and star-formation in mini-haloes, but weak enough that the IGM spin temperature has not yet decoupled from the CMB. Note that mini-haloes will only be visible in portions of the IGM which have *never* been ionized; mini-halo formation in fossil H II regions is strongly suppressed (Oh & Haiman 2003).

Detection of a 21-cm spectral signature in absorption against a high-redshift radio loud source (Carilli et al. 2002; Furlanetto & Loeb 2002) will not suffer from the foregrounds discussed here, except for the rather speculative possibility that intervening high-redshift discs could give rise to a plethora of obscuring radio recombination lines. Of course, this ‘foreground’ would itself be a marvellous window on the high-redshift universe! The main difficulty of absorption studies, of course, is whether such bright radio sources exist at early times, when structure formation is in its infancy.

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ing out that H α observations with JWST could identify free-free sources below the SKA flux cut-off.

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